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LASER-INDUCED SPALL IN SILICON CARBIDE

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This article presents an alternative (or additional) test technique to investigate ceramic spall strength. The test uses a laser beam to produce the impact conditions for spall. The test configuration consists of a ceramic target covered by an opaque material (usually black tape) followed by a transparent material (usually water). The laser first passes through the water and vaporizes a thin layer of the black tape. The vapor absorbs the remaining laser pulse and creates a rapidly expanding plasma plume. The plume is trapped between the ceramic surface and the water creating a high-pressure, short-duration pressure pulse. The pressure pulse produces a compressive shock in the ceramic which travels through the specimen, creating a tensile (spall) stress near the rear surface after its reflection. Although there is substantial heat generated during this test, it is important to note that the applied stress is produced mechanically (like the plate-impact test) and not thermally. Some advantages of this technique are that it is relatively inexpensive to perform, the applied pressure profile (shock stress) is easily changed, the results are very reproducible, and the targets are not destroyed during testing. This paper presents a discussion of the experimental technique, including test results for silicon carbide. Computations of the experiments are also presented that further validate the JHB model and help analyze the data.

INTRODUCTION

There continues to be much interest in incorporating ceramic materials into armor systems. To support the armor design process there is a need to obtain certain ceramic material properties for use in material models and computer codes. One important ceramic material property is its spall strength. Spall strength is the maximum tensile stress the material can withstand under uniaxial strain conditions and has historically been determined using 1D plate-impact experiments. Although plate-impact experiments produce well-defined spall data, they are relatively expensive and time-

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consuming to perform. This paper presents an alternative (or additional) test technique that can be used to determine the spall response/strength of ceramic materials.

The remainder of this paper presents a discussion of the experimental technique, including test results for silicon carbide. Computations of the experiments are also presented and are used to further validate the JHB model [1] and help analyze the data. Lastly, computations are presented that investigate the sensitivity of ceramic tensile strength and its effect on spall formation.

EXPERIMENTAL TECHNIQUE

The experimental technique uses the Laser Shock Peening (LSP) process [2, 3] to produce the impact conditions for spall. The LSP process was originally developed for the aerospace industry to produce residual surface stresses in metal parts. Residual compressive surface stresses have been shown to significantly increase the fatigue life of metals and metal alloys. As presented herein, another proposed application for the LSP process is to produce spall in ceramics. A schematic of the test set-up and loading process is presented in Figure 1. The test configuration consists of a ceramic specimen covered by an opaque material (black tape) followed by a transparent material (water). A description of how the experiment works is as follows: 1) The laser beam first passes through the water (transparent to the laser) and vaporizes a thin layer of the black tape. 2) The vapor absorbs the remaining laser light and creates a rapidly expanding plasma plume. 3) The plasma plume is trapped between the water and the ceramic and creates a high-pressure, short-duration pressure pulse. 4) The pressure pulse creates a compressive shock in the ceramic which travels through the specimen, creating tensile stresses near the rear surface after its reflection. If the tensile stresses exceed the tensile strength of the ceramic, the material will fail and spall will occur. Although there is substantial heat generated during this test it is important to note that the applied stress is produced mechanically (like the plate-impact test) and not thermally.

A typical pressure-time history profile produced by LSP is shown on the left side in Figure 2. The pressure is applied very rapidly, with a rise time of approximately 4 ns, and gradually is reduced over the next 40 ns. The peak pressure, which is primarily a function of the laser intensity, can be varied from about 1 GPa to approximately 12 GPa. The duration of the pressure pulse can also be modified by using different laser pulse lengths [2]. A significant feature of the LSP technique is that the target is not destroyed during testing and can thus be evaluated post mortem. Figure 3 shows the back surface of a tested target where a circular spall zone is produced. Another feature of the LSP process is its ability to produce consistent, repeatable results on a single specimen. Figure 4 shows the back surface of a ceramic target that has been tested nine times, using three different peak pressures. Note the consistency in the diameter of the

spall zone for each of the peak pressures used. By using one specimen for multiple tests the experiments can be performed quickly and inexpensively.

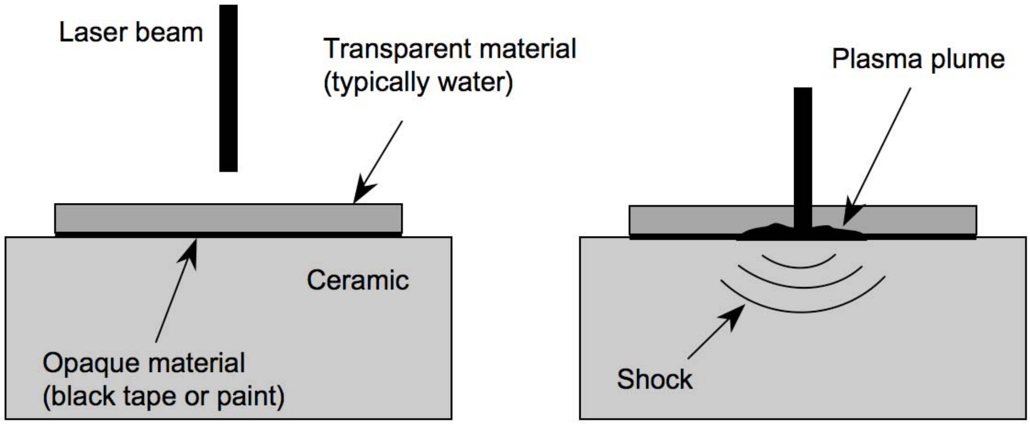

Figure 1. Initial test configuration and loading process for the Laser Shock Peening (LSP) test.

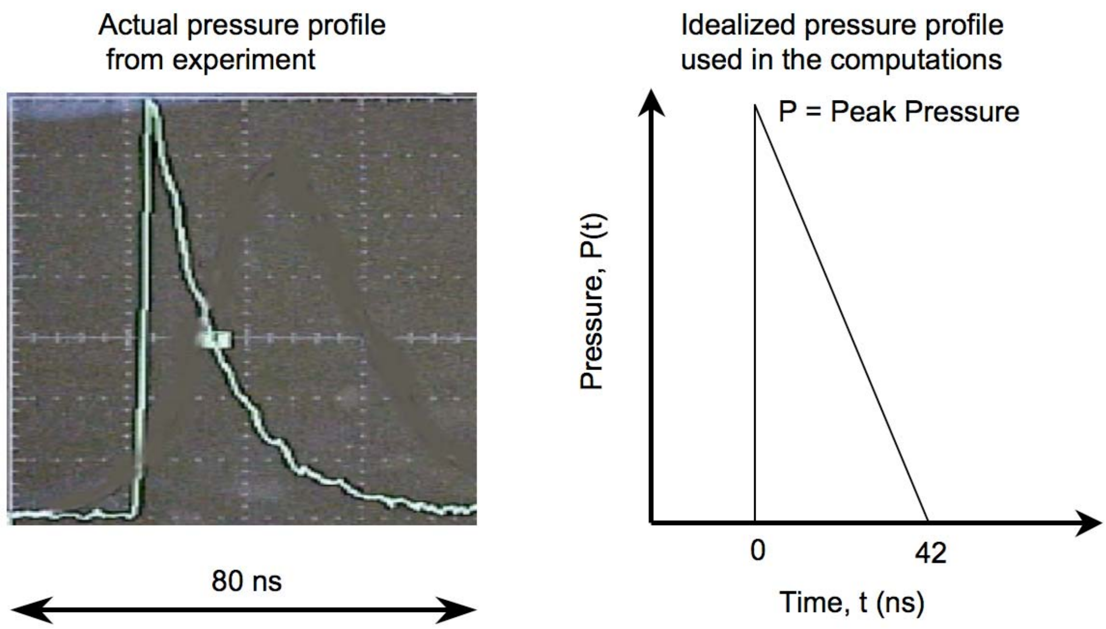

Figure 2. Actual and idealized pressure profile produced from the LSP experiment.

EXPERIMENTAL AND COMPUTED RESULTS FOR SILICON CARBIDE

The material used in this work is a hot pressed silicon carbide (SiC) produced by Ceradyne Inc. of Costa Mesa, CA. The SiC is 98.5% pure, its density is $\rho = 3.20$ g/cm^3, Young's modulus is E = 450 GPa and Poisson's ratio is $\nu = 0.17$ as provided by Ceradyne Inc. Three experiments were performed and the results are presented in Figure 5. Experiment 1 used a SiC target that was 6.4 mm thick and a peak pressure of 3.7 GPa. Experiments 2 and 3 used targets that were 12.8 mm thick and peak pressures of 3.8 GPa and 4.5 GPa respectively. The pulse duration was approximately 42 ns for all three experiments.

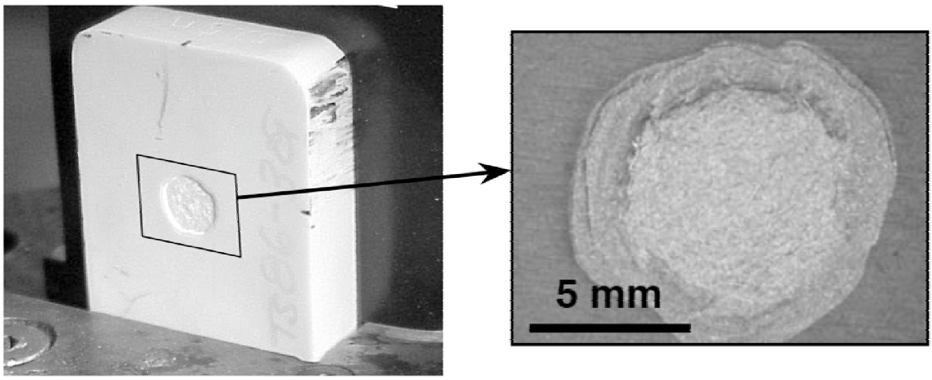

Figure 3. General example of a tested ceramic target showing the circular spall zone on the rear surface.

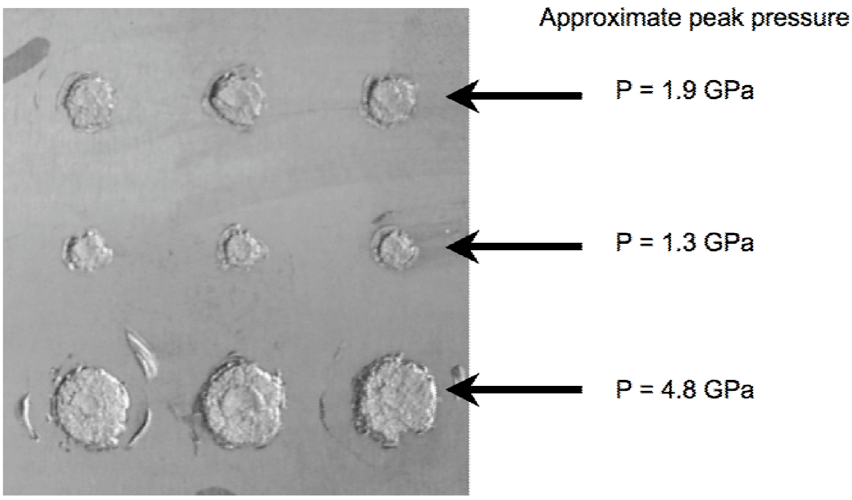

Figure 4. Rear surface of a tested ceramic target showing nine circular spall zones from nine experiments. Three experiments used a peak pressure of P=1.9 GPa, three used P=1.3 GPa and three used P=4.8 GPa.

Figure 5 shows the cross section of each target after testing. Experiments 1 and 3 produced well defined spall zones where a portion of the rear surface was removed during the spall process. Experiment 2 produced a spall plane, but no material was removed. Experiment 2 was very near the spall threshold.

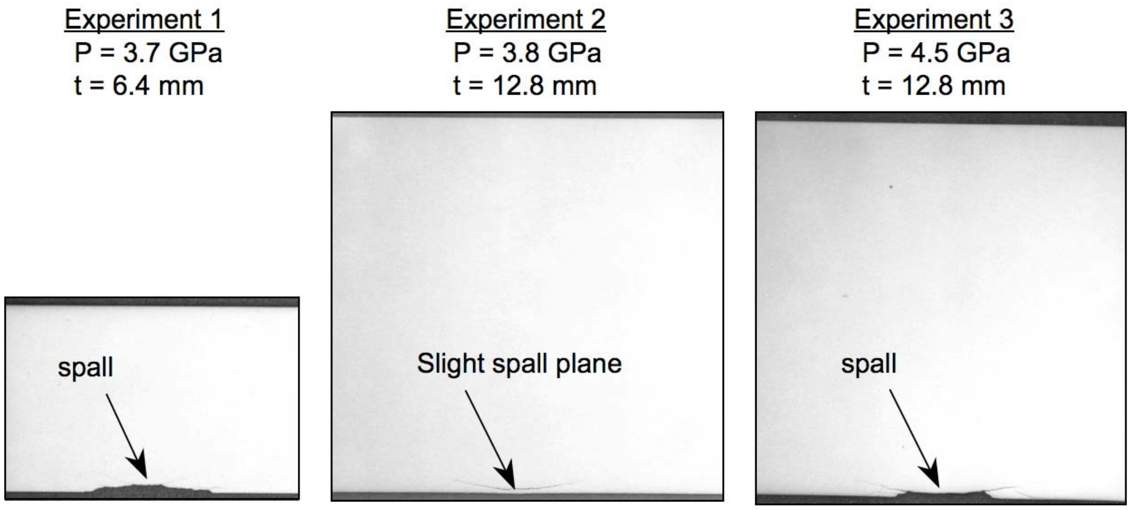

Figure 5. Experimental results for three silicon carbide targets. Shown are the cross-sections where the impact side is at the top, the spall plane is at the bottom, and the vertical dimension is t.

Computations of the three experiments were performed using the JHB model and constants for silicon carbide [1]. The initial geometry is presented in Figure 6. The computations were performed in 2D axisymmetry using the EPIC code. The pressure pulse was applied to the front surface, over a 5-mm diameter, using the idealized pressure-time history presented on the right side of Figure 2. The time duration used for the pressure pulse was 42 ns for all three experiments. Figure 7 shows the computed result for experiment 1, where the net axial stress is shown propagating through the SiC at t = 0.04 μs, t = 0.30 μs and t = 0.50 μs. Note the attenuation of the stress pulse as it passes through the target. The lower right portion of Figure 7 shows material damage at t = 6 μs (late time in the computation) and clearly shows the material failing at the rear surface and the formation/separation of a disk of material (spall disk). Figure 8 presents a comparison of the three computed results to those of the experiments (enlarged for clarity). The computed results are shown above the experiment using the same scale. The computed result for experiment 1 compares well to the experiment showing spall with a similar diameter and geometry. The computed result for experiment 2 also compares well to the experiment where both produce a slight spall plane within the

material, but no material separation (spall disk). The computed result for experiment 3 shows a clear spall plane, but the failure does not quite make it to the rear surface, thus no material is separated. The experiment shows spall including a loss of material.

Lastly, computations were performed to determine the sensitivity of the spall formation to changes in the tensile strength. Figure 9 presents three computed results using different SiC tensile strengths. The computations use the configuration and pressure profile from experiment 2. The tensile strengths used were T = 0.375 GPa, T = 0.75 GPa (this is the published value from reference 1) and T = 1.125 GPa. The results show a significant difference in the diameter of the spall zone although it is interesting to note that none of the results produced material separation (spall disk). It also appears that the computed result using the published tensile strength, T = 0.75 GPa, produces the best result when compared to the experiment. If the tensile strength of a ceramic was not known, this computational approach could be used to "back out" the tensile/spall strength. Alternatively, a Velocity Interferometer System for Any Reflector (VISAR) [4] could be incorporated into the test configuration to provide traditional wave profile data to determine the spall strength.

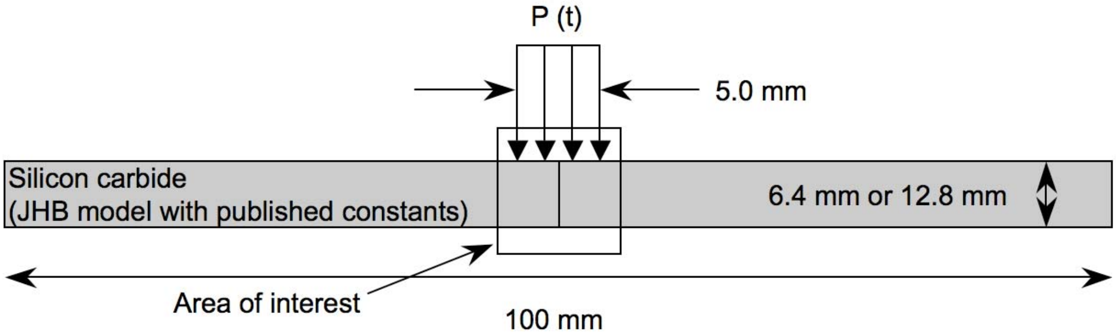

Figure 6. Initial geometry for the computations.

SUMMARY AND CONCLUSSIONS

This paper has presented an alternative (or additional) test technique to determine ceramic spall behavior. The technique uses a laser beam to produce the impact conditions for spall. The target consists of ceramic covered by an opaque material (black tape) followed by a transparent material (water). Some advantages of this technique are that it is relatively inexpensive to perform, the applied pressure profile (shock stress) is easily changed, the results are very reproducible, and the targets are not destroyed during testing. Computations of three experiments were also presented and compared well to the experiments providing further validation to the JHB model. Lastly, computations were presented that investigated the sensitivity of the SiC spall

response to variations in tensile strength. The results showed that the diameter of the spall plane changed significantly when the tensile strength was changed.

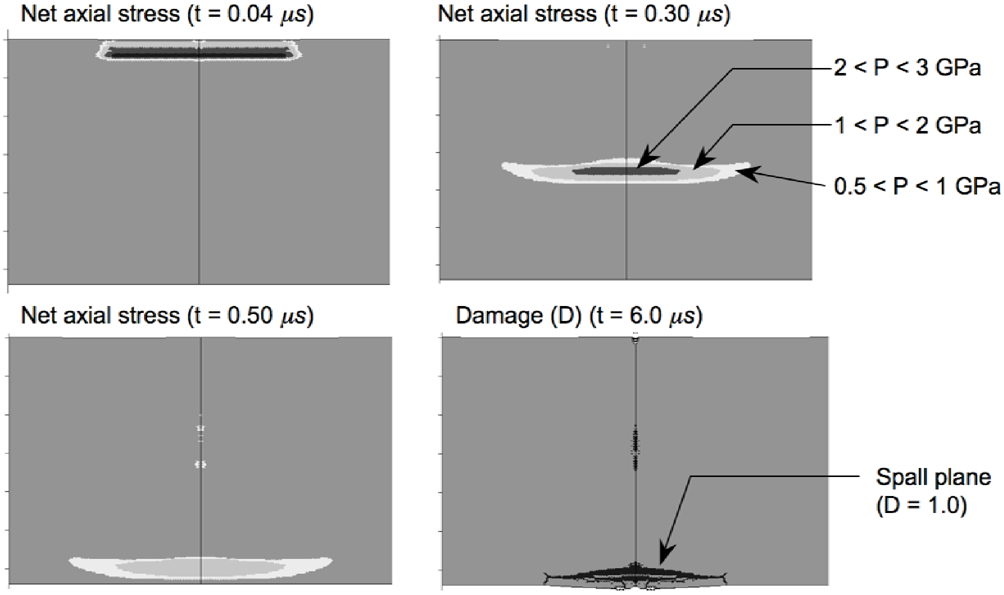

Figure 7. Computed results for experiment 1 showing net axial stress contours at t = 0.04 μs, t = 0.30 μs, and t = 0.50 μs. Also shown is damage at t = 6 μs which clearly identifies the spall zone.

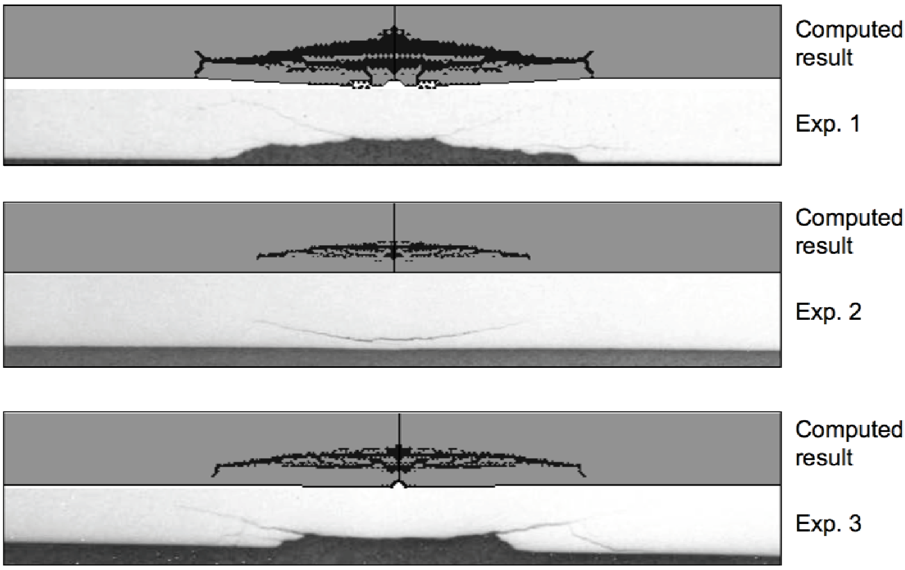

Figure 8. Comparison of computed and experimental results for three silicon carbide tests.

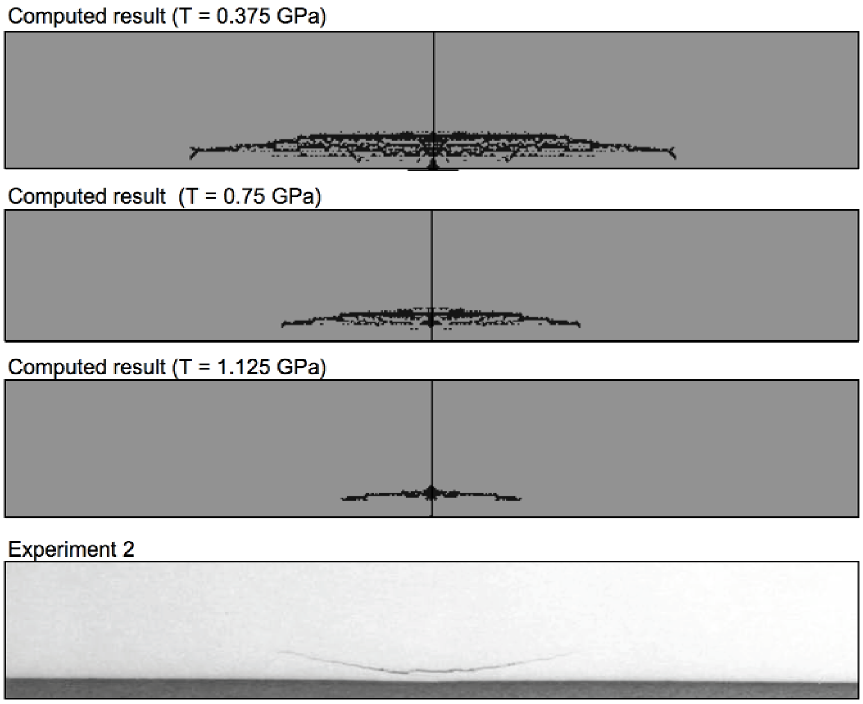

Figure 9. Computed results for experiment 2 showing the sensitivity of the spall zone to changes in the material model tensile strength.

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